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Plant Disease Forecasting
PAUL R. MILLER AND MURIEL O'BRIEN 547

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THE BOTANICAL REVIEW

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PLANT DISEASE FORECASTING

PAUL R. MILLER AND MURIEL O'BRIEN

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INTRODUCTION

The following review is concerned with the history and procedure of forecasting the probable seasonal incidence of various plant diseases as a practical method of lessening the seriousness of their effects. For the purposes of this summary, " forecasting " is defined as follows: Forecasting involves all the activity in ascertaining and notifying the growers of a community that conditions are sufficiently favorable for certain diseases, that application of control measures will result in economic gain or, on the other hand, and just as important, that the amount of disease expected is unlikely to be enough to justify the expenditure of time, energy and money for control. Thus this review covers the scientific foundation for predictions, those services conducted as a practical aid to growers, and the investigations pertaining to forecasting that are now in progress.

A great deal of work has been done on topics included in the range of interest of forecasting, but which so far has not been put to actual use in practical forecasting. In some cases results of these studies help to interpret observations on spread, incidence and importance of diseases for which forecasting is a regular practice. To that extent they are relevant to this discussion and are cited in corresponding sections. Where such studies, however basic, have so far only a general bearing, no attempt has been made to cite them. For example, the relation of plant disease occurrence and importance to temperature, moisture and other environmental conditons is certainly a relevant topic, but by far the greater part of the voluminous literature has no specific application for the purpose of this review. Similarly spore dissemination, rate of disease spread and other epidemiological studies, unless they have been applied in working out criteria for or interpreting results of forecasting as a practical aid in plant disease control, are not reviewed in this discussion.

The economic value of forecasting is obvious enough. Some consideration should be given, however, to its position as a part of

the science of plant pathology. All sciences reach a point where future real progress, as distinguished from mere accumulation of additional information, depends on the organization of the separate blocks of knowledge and application of them to accomplish practical results. It will be seen that forecasting is one of the ways of achieving such a synthesis. It is this inherent constructive feature that makes the development of forecasting one of the most interesting and rewarding phases of plant pathological investigation.

APPLE AND PEAR SCAB

Interest in forecasting the time of development and severity of apple scab (*Venturia inaequalis* (Cke.) Aderh.) and pear scab (*Venturia pirina* Aderh.) for efficient use of spray materials and prevention of crop loss had its beginning about one-quarter century ago.

Outside the United States and Canada.

PHENOLOGICAL BASES FOR FORECASTING. The relationship between apple scab and environmental factors was first noted as being important in proposing a spray program early in the 1920's. The first weather factor studied was rainfall. Bremer (1924, 1926*a*, *b*), in his analysis of meteorological data, found a distinct connection between rainfall during the first ten days of May and the incidence of scab in the Proskau district of Silesia. The amount of rainfall in this period before the opening of the blossoms seemed to determine the incidence of the disease, heavy rains at this time generally denoting a severe epiphytotic the following summer.

About 24 years later Louw's (1947*a*) studies indicated that increased incidence of apple scab in South Africa in the middle 1940's was not correlated with the corresponding higher rainfall and that other factors might predominate over the effect of wet conditions. In the winter-rainfall area of the Cape region of South Africa, initial source of infection is from fallen infected leaves (Louw, 1947*b*). He pointed out (Louw, 1947*c*) that winter temperatures exerted a dominating influence on the epiphytology of scab in South Africa, apparently accounting for variations in severity from year to year, with severe outbreaks coinciding with relatively low winter temperatures. The data from these studies provided a basis for estimating in advance the probable severity of

the disease in any particular season and made it possible to warn growers in localities where severe outbreaks would likely occur.

Owing to the shortage of fungicidal materials, spray warnings during World War II were of greater importance than before the war. Darpoux (1943) concluded that methods of issuing spray warnings depended too much on empiricism and on personal experience, and proposed a systematic scientific study of the effects of environmental factors on the biology of the apple scab organism. The results, he felt, should be reduced to laws and expressed in graphic form. Critical stages of susceptibility should be studied, phenological data obtained and a relationship established between the development of a given pathogen and that of other parasites or of higher plants.

Information obtained from the study of the effect of natural environment on disease incidence and development led to proposals for prediction of appropriate dates for spraying according to ascospore discharge and bud development (Holz, 1939*a, b;* Hus, 1942; Jahn, 1943; Van de Pol and Flipse, 1949). Spores were trapped under both laboratory and out-of-doors conditions, and the results compared from time to time. In Holz' experiments (1939*a*) the first spores were trapped in the laboratory eight days prior to the first spores trapped in the open following rain. An immediate notification to growers of the laboratory results would thus enable them to utilize the interval regularly elapsing between indoor and outdoor ascospore production for the beginning of the first and important fungicidal treatment.

From seven years' observations, Holz (1939*b*) found the average dates on which perithecia ripened in Altenland, Germany. Temperature aggregates, based on mean daily temperatures, were calculated for each year from the first or fifteenth of each month between November and April to the date of ripening of perithecia. The temperatures before the first of March had no appreciable effect upon ripening of the perithecia. From March 1 onwards until perithecia ripened, the mean day temperature aggregrates were almost constant during the seven years. They were on the average 105° C, whereas temperature aggregates from earlier or later dates differed considerably. Holz concluded that the sooner a mean day temperature aggregate of 105° C is reached after the first of March, the sooner the perithecia will ripen. Jahn (1943)

tested the practicability of Holz' methods for prognostication of the beginning date of ascospore discharge on which to base the spraying schedule. Since his observations confirmed those of Holz', that under outdoor conditions spore discharge commenced a few days after the initial discharge of spores on overwintered leaves tested in the laboratory, Jahn concluded that appropriate dates for spraying could be predicted reliably on this basis.

Hus (1942) objected to using ascospore discharge as a signal for spray warnings because of six points: (*a*) ascospore discharge in one locality does not necessarily coincide with the same process in other places where rain may fall on different dates during the critical periods in April and May; (*b*) unfavorable spray conditions might obtain at time of ascospore discharge, and once infection is established, it is very difficult to suppress; (*c*) treatment of large areas required days so that even in fine weather part of the orchard may be reached too late; (*d*) spraying could not be carried out on a cooperative basis; (*e*) if spraying is done as soon as perithecia mature, too long an interval might elapse between treatment and discharge under the influence of rainfall, the exact date of which can seldom be predicted several days beforehand; (*f*) mixed plantings might have perithecia ripening sooner on the leaves of one variety than on another, and, therefore, several ascospore discharges would have to be considered in fixing the spraying dates.

ECOLOGICAL BASIS FOR FORECASTING. Louw (1947*c*) observed that early leaf fall during the dry period of the year in South Africa severely restricted the amount of infection during the subsequent year as the fungus cannot survive such dry conditions in the fallen leaves. Conversely, when leaves were retained longer, epiphytotics were likely to occur the following spring.

WARNING SERVICES FOR SCAB CONTROL. Several warning services are now being conducted abroad for apple scab control. In a report of the Cawthron Institute (1941), New Zealand, mention is made of a notification service for the benefit of growers in the Nelson area in connection with scab control. In Australia a warning service is conducted for the prevention and control of apple scab (Magee, 1950) [1]. In Norway investigations are to be con-

[1] In order to make this review as current and comprehensive as possible, the writers corresponded with many pathologists and research workers in foreign countries, requesting them to call attention to unpublished papers

ducted on the ascospore spread of apple scab during 1951–1953 with the purpose of establishing a warning service for this fungus (Jørstad, 1950).

Fruit spraying in England is based on a calendar depending on the stage of development of the leaf and flower buds, and no apple scab warnings are considered necessary (Gregory, 1950*a*).

In Holland (Quanjer et al., 1942; van de Pol, 1948; van de Pol and Flipse, 1949) an apple and pear scab spray warning service, timed according to the dual criteria of ascospore liberation and bud development, was instituted in 1948. This service is based on laboratory examination of leaves collected shortly before the first ascospore discharge and examined after four- and 24-hour intervals. Six to eight days after the beginning of profuse ascospore discharge under the warm and humid conditions prevailing in the laboratory, abundant spore "flight" may be expected in the open. Eight years' observations in five Provinces revealed no material discrepancies in the dates of ascospore liberation. Also the stage of development of the buds was taken into consideration. Since bud development is dependent upon weather conditions, close daily contact then is maintained between the Meteorological Institute and the Plant Protection Service. The spray warnings are promptly included in the wireless weather reports and distributed as well in other ways. Continued research on the problem (Vlasveld, 1951) is being carried out on conditions favoring infection. Field surveys in 1949 in several districts contributed to the solution of certain problems. Also, more exact data were accumulated on the number of leaves which would be examined per day early in the season to gain a reliable insight into the general maturation of the perithecia for improvement of spray timing and issuance of warnings.

Vullings (1950) reports a severe apple scab epiphytotic in 1949 in Holland, resulting in a loss of 1,000,000 gulden to growers in the Limburg region. According to the author, crop failure is nearly always attributable to unduly long intervals between treatments. Omission of one treatment at the decisive blooming period cannot be retrieved by three or four summer sprays.

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or work in progress in their country on the subject of forecasting plant diseases. Numerous informative and pertinent replies were received, for which the writers are very grateful. The content of these letters has been incorporated in this review and cited in the literature.

In the United States and Canada.

While European countries were exerting vigilance in preventing losses from scab by various methods of prediction, American and Canadian pathologists were similarly concerned. Spray information services, with special reference to the control of apple scab, were organized in New York, Delaware, Ohio, Indiana, Illinois, Kentucky, Wisconsin, West Virginia, western and eastern Canada (Adam, 1927; Adams, 1934; Coulson and Godbout, 1930; Crosby, 1932; Eastham, 1930, 1931; Godbout, 1951; Heuberger, 1951; Howitt, 1932; Keitt, 1926; Leach, 1951; Ohio Agr. Exp. Sta. Bull., 1927, 1928, 1934; Parks, 1932; Pierstorff, 1932; Robertson, 1929). For the most part, these programs were based on a careful study of the interactions between weather and disease. By studying the development of the fungus under both laboratory and field conditions (Young and May, 1927), it was possible for these workers to determine in advance when and under what conditions apple scab is likely to occur in their particular regions. This knowledge, plus that of the stage of fruit bud development and conditions of tree growth, is correlated with the local weather forecasts in the United States and Canada. On these three factors, in combination, spray warnings are based and issued to growers.

The organization of all these spray warning services follows somewhat the same pattern. From observations made by trained pathologists, entomologists and county extension workers, growers are notified by letters or cards as to the most opportune time for spraying, oncoming rain periods, recommendations concerning materials and strength of spray materials to be used, and modifications in the sprays for special varieties of apple. The alerted grower awaits telephonic or similarly rapidly conveyed messages as to exactly when to spray or dust. The radio has been an important aid in disseminating this information, and messages so sent are keenly awaited and followed by growers. These rapid messages are usually confirmed by card sent through the mail the next day.

The grower, in many cases, keeps records of the success or failure of his spraying. Percentage of clean fruit and yields are also studied. When loss is caused by inadequate spraying, recommendations are made by trained specialists for correct application of sprays in his particular orchard for future seasons.

In eastern Canada the Province of Ontario began its spray service in 1924 (Howitt, 1932). The service covered two districts, one for the Niagara district which included tender fruits such as peaches, and the other for the rest of the province and chiefly concerned with apples. Spray recommendations are made under the direction of staff members of the Ontario Agricultural College, and the details of the operation are carried out by local supervisors, usually one to each county. The service is free to any grower, the one requirement being that the grower have adequate spray machinery.

In the Province of Quebec an orchard spray service was inaugurated in the spring of 1929 by the Provincial Department of Agriculture (Godbout and Coulson, 1932). Spray information is based on microscopic examination of perithecia on old leaves collected at two- and three-day intervals. The first spray depends on the time of maturing of perithecia and ascospores. Subsequent sprays are recommended according to host development and weather conditions. Godbout (1951) reports that, since it is now known that ascospore discharges occur each time there is sufficient rain, cards are sent to growers in advance of the time when each spray should be applied. These cards contain information on spray formulae to use and various remarks regarding treatment.

In western Canada a spray warning service for apple scab was instituted on a small scale in the Kootenays in 1929 (Robertson, 1929). Growers were advised to apply the first spray just as the ascospores on old leaves reached maturity. If the first application was postponed until pink stage, secondary infection occurred. In the second report on this service (Eastham, 1930), which uses time of spore maturity and discharge and weather forecasts as criteria, it was noted that meteorological observations were of considerable value in fixing the time of the first spray and in determining dates of probable heavy infection, but that reduction in the number of sprays seemed to be an undue risk.

VINE MILDEW

ITALY. Almost concurrently with the organization in Europe of a forecasting system for apple scab control, a vine spray warning system was organized in western Europe for the control of *Plasmopara viticola* (Berk. & Curt.) Berl. & de Toni. Like apple scab,

the forecasting of vine mildew was set up on the basis of the relation of meteorological conditions to the development of the fungus. The appearance of the first infection as "oil" spots on the leaves was also watched, but, for the most part, forecasting was based on phenological data.

In connection with forecasting according to the weather conditions likely to influence disease outbreaks, in 1921 (Voglino, 1922, 1924) fortnightly bulletins were compiled from meteorological data on conditions capable of influencing epidemics of the fungus diseases of the vine in the Provinces of Turin, Cuneo and Novara, Italy. The reports from these three Provinces were sent to a central pathological station in Turin, which issued preliminary instructions for preventive treatment as soon as information received indicated favorable conditions for germination of the winter spores and for first infection of the vines. Later instructions were issued for appropriate treatment at each successive stage of attack in accordance with rainfall and other weather factors.

The number of these stations in one Province, Allessandria alone, was 53 (Briciole, 1929), and in 1929 (Manzoni, 1930) similar stations were set up in the Province of Treviso. In 1936 (Montemartini, 1936) a forecasting system was organized in Sicily. Interest in broadening the scope of anti-mildew observatories continues to the present writing (Baldacci, 1947*b;* Baldacci and Orsenigo, 1950; Malfatto, 1950; Renato, 1950).

A specific meteorological phenomenon that interested Italian workers as a basis for forecasting was dew point estimation. In the vicinity of Perugia (Corneli, 1932) records were taken on dew point, or that temperature at which atmospheric moisture is condensed, thus bringing about favorable conditions for the germination of zoospores. If the dew point was higher than 12° C, the lowest temperature at which germination takes place, an outbreak of vine mildew might be expected. From his experiments Corneli concluded that the presence of condensed moisture was the predominating factor conducive to an attack of mildew, particularly in central Italy where average daily temperature in late spring and summer favors infection, and that the safest procedure for effective forecasting would be to couple direct observation of conditions leading to the condensation of moisture with thermometric and psychrometric data on atmospheric changes.

The stage of development of the fungus on the host was also used as a forecasting sign, growers being advised to begin spraying when first infections showed as "oil spots" on the leaves.

Baldacci (1947*a*), in applying Müller's incubation calendar (loc. cit., vine mildew forecasting in Germany) in northern Italy for the determination of treatments, found that the pathogens required a shorter incubation period during May than that prescribed by Müller's calendar. High atmospheric humidity was found to be an important factor in shortening this incubation period. Further studies (Baldacci, 1948–49) indicated that the incubation periods are the same in every locality along the northern slope of the Appenine chain and that the regions of northern Italy and of Tuscany can avail themselves of the incubation calendar to advantage as a means of controlling *P. viticola.* However, according to the observations, in regions where fog and dew are prevalent, applicability of the calendar is limited to the first treatments. In using the incubation calendar in southern Italy and Sicily, there is need for further study on the relation of climatic conditions to outbreaks before the method can be usefully employed in this area (Baldacci and Orsenigo, 1950).

The effectiveness of these forecasting systems is reflected in the satisfactory results obtained in control where treatments of vine mildew were carried out according to instructions. Up to one-half the usual number of sprays could be omitted, with consequent savings in time, cost, fungicidal material and energy under the proper conditions, usually of dry weather (Rossi, 1934; Rui, 1935; Petri, 1936; Trotter, 1936). However, Manzoni (1932*a, b*) concluded that recommendations made by mildew forecasting stations in certain parts of Treviso Province would be of little value in areas where there is a constant tendency to infection, even in dry seasons. Manzoni also concluded that number of sprays needed varied less than might be supposed from different intensities with which vine mildew develops. But in another vein, where growers persisted in using the full number of sprays recommended for wet seasons under conditions of scanty rainfall, wastage in one instance of 90 million lire was reported (Gabotto, 1928).

FRANCE. The operation of a French vine warning service paralleled the Italian service. There are five noted stations, viz., Bordeaux, Montpellier, Clermond-Ferrand, Avignon and Antibes. At

a station established much earlier in Cadillac, critical times for notification had been studied since 1898.

The French vine mildew forecasting and warning service was another service based on the interrelation between meteorological factors and disease appearance and development, dew, mists and nocturnal rain being among the factors favoring infection (Institut des Recherches, 1933). The Bordeaux (Schad, 1936) method of forecasting, devised by Cazlaux-Cazalet and Capus, probably adhered most closely to a strictly phenological basis for forecasting. At this station earliness and intensity of infection were determined by a study of the November–April rainfall. Predictions for secondary infection were based on spore prevalence and amount of rain. Forecasting could thus be done well in advance of attack.

In developing a scheme for reducing safely the number of treatments to a minimum, specimens collected from local observation posts during March, April and May are examined in the Station laboratory (Schad, 1943*a, b*), and the progress of oospore germination is determined under local conditions. Prediction of the primary period of infection is based on presence of active oospores, temperature above 11° C and a rainy period keeping the surface of the soil wet for several days. By following the temperature and rainfall and by knowing the abundance and germinative capacity of the spores, it was found possible to predict the extent of first infection. Secondary infections are dependent upon active conidia, rain and a temperature over 8° C. Persistence of water on the leaves for six or more hours at a temperature between 11° and 20° C will inevitably induce infection. The number of treatments required is determined by the extent of primary infections, coincidence of conidial formation with rain, the amount of rainfall in June and July, and the critical stages of vine growth. In the calculation of time for incubation, the appearance of infection spots can be determined with greater accuracy if only six hours in which the relative humidity is over 60 per cent are considered.

At Montpellier Branas' (Schad, 1936) method was based mostly on data afforded by the vine itself and on biometrical, pathological, climatological and cultural factors (Branas and Bernon, 1934). Germination of overwintered oospores under natural conditions was the signal for spring renewal of the disease. Primary infection was also based on oospore germination, with incubation periods

of nine days for the first cycle and seven days for the later cycles. A later report (Branas, 1939) pointed out that temperature did not appear to be the important factor locally in determining the length of the incubation period, but that the chief influence was the water content of the tissues. Lesions on tied vines contained more water than others not so treated and were three times as large as those on untied vines. It was suggested that some relation probably exists between severity of attack, size of lesions, duration of incubation and the degree of turgescence of the tissues (ibid., Schad, 1936, Bordeaux calculation of incubation period).

At Clermond-Ferrand a combination of the Bordeaux-Montpellier methods was used (Schad, 1936).

The mechanics of conducting this service in the early days was the relay of warnings or reports by visual or sound signals (Chaptal, 1923). Later these reports were sent as code telegrams at minimum cost to subscribers, giving information on spray warnings, the weather, appearance of pests, etc. In 1931 the Bordeaux Climatological Station had 1,425 subscribers, the number dropping slightly to 1,236 in 1932. At Clermond-Ferrand the number of subscribers was 525 in 1932 (Institut des Recherches, 1933).

Warnings based on first infections appearing as "oil spots" on the leaves were not considered reliable in France.

Excellent practical results have been obtained under the French spray warning service, as shown in the reduction of the empirical number of five or six spray applications to one or two when no more are needed, thus conserving spray materials in times of shortage. In 1938 spray warnings resulted in a saving of spray materials in southwest France valued at 200 million francs (Darpoux, 1949). In 1941, when copper sulfate was very scarce, growers who ignored the spray warning service sprayed too soon, with the result that their crops were ruined by late outbreaks of mildew. However, if no spray warnings had been issued that year, losses incurred would have run into thousands of millions of francs. On the whole, two spray applications a year are saved under the system, or 20 kg. copper sulfate per hectare. For the whole of France this amounts to 30,000 tons or, under the present monetary conditions, 2,500,000,000 francs a year, not counting cost of labor and depreciation of machinery. Many growers consider that these diseases, including also apple and pear scab, are now readily controlled through the services of the spray warning system.

French observers have also pointed out an interesting note on fungus ecology as a basis of a forecast. They found that the first attack of sycamore (*Plantanus occidentalis* L.) by the anthracnose fungus (*Gnomonia veneta* (Sacc. & Speg.) Kleb.) regularly precedes the first attack of vine mildew by several days and can be used as an index of approaching vine disease (Darpoux, 1943).

GERMANY. The vine spray warnings system in Germany was built up on a long-term study of phenological conditions in relation to the development of the disease and on realization of the value of these phenological data in connection with the establishment of experimental stations for forecasting attacks of vine mildew. Müller (Müller, 1930, 1931, 1936, 1937, 1938; Müller and Sleumer, 1934) developed an "incubation calendar" in 1913. The calendar acts as a guide to timely spraying, based on temperature and moisture conditions and on their effect on the future development of the disease. The incubation period of the disease was found to vary from five to 18 days, depending on the interaction of weather conditions. The value of the calendar, particularly under conditions obtaining in the Baden vineyard area, has been reflected in the average increase in yield of 135 per cent in the period 1919 to 1938, and in the accuracy with which correct spraying times were predicted for the period from 1913 to 1938. The system appears to have achieved a great degree of reliability, and French criticisms of the calendar (Müller, 1937) were considered to rest on misinterpretation of the principles involved and failure to recognize certain fundamental differences between laboratory experiments and practical field work.

GREECE. The question of agricultural warnings in Greece is undergoing investigation (Ayoutantis, 1950; Zachos, 1951). L'Institut Phytopathologique Benaki has had in view for a long time the study of certain phases of the biology of *Plasmopara* in the different vine-growing regions of the country, with the possibility of organizing warning stations and applying in Greece the methods used and approved in other grape-growing countries, particularly France. These stations will give to grape-growers provisions permitting proper application of treatments at the opportune time. Unfortunately the events of war, followed by occupation of the country and disturbances of the following years, prevented realization of this plan until 1949. In that year the project was estab-

lished under the direction of the Laboratoire de Mycologie de l'Institut Phytopathologique Benaki, Kiphissia-Athènes. In 1950 the first observations were made, in Peloponnesia, in the region of Corinth. In this region viticulture is excellent and the grape-growers are the most advanced in the country. This one year's work of correlating weather conditions and the development of *Plasmopara* with the stages of development of the vine, in particular the critical stages, showed that three applications of dusts were sufficient for protection of the vineyards in this region. This afforded a reduction in treatments of more than 50 per cent with consequent economy of copper sulfate, not to mention time and energy. It is planned to continue the study with the hope of organizing as soon as possible the warning stations necessary to protect the vineyards with certainty from this most formidable of diseases.

RUSSIA. One phase of vine mildew forecasting work in Russia was based on the " incubation calendar " of Müller with modifications to suit different growing areas and climatic conditions. Oltarjevski (1931) accumulated data on meteorological details in 1929 in the Derbend region. From these data he constructed a preliminary " incubation curve " of the vine mildew disease for this region, pointing out the deviations of this curve from that established by Müller. According to the author it was entirely feasible to work out for different vine-growing regions in the world, in any given year and under any given set of climatic conditions, bases on which mildew outbreaks could be predicted. Later work with a small range of controlled experiments supported this view (Oltarjevski, 1934) that Müller's " incubation curve " would not be applicable under all sets of climatic conditions and should be corrected to suit the local conditions prevalent in different regions. In the Caspian region and the Caucasus it was found that spring outbreaks of vine mildew occur after periods of three or four days during which night minimum temperature does not go below 10° C, all other meteorological conditions being favorable for development of the disease. Strong winds were found to have a desiccating effect on the leaf moisture and to be a limiting factor in the development of outbreaks.

The modified formula, suitable to environmental conditions in the vine-growing areas of U.S.S.R. (Shatsky, 1935), is given as $p(t-8) = 60$, p being the length of the incubation period and t the average mean daily temperature for the period. This formula is

employed between 10° and 24° C. Greater precision at the lower range is obtained by the following formula:

$$p = \frac{60(t-8)}{(t-16)64D}$$

p = the number of days of the incubation period
t = mean day temperature on the day when infection occurred (obtained from long-term weather records)
D = increase in mean daily temperature for 30 days (obtained from long-term weather records)

In order to calculate dates of treatment, using the graphic simplification of Müller's curve, a calendar of incubation periods was compiled for the locality to be studied, using temperature data of many years' record and these equations. On the abscissa are marked the days when the incubation period begins, on the ordinate when the incubation period ends. The curve drawn through the intersections will delimit the number of incubation periods for a given locality, and the theoretical end of the incubation period from any starting point can also be fixed on this curve. The lengthening of the incubation period by days with minimum temperature below 13° C can also be reckoned by drawing the values of such minimum temperatures in a straight line parallel to the abscissa of the graph. For determination of the course of the incubation periods, a special table, compiled on the basis of the equation of Müller's curve, is employed, viz.:

$$\frac{1}{n} = \frac{t-8}{60}$$

where $1/n$ = one day's value of the length of the incubation period (in percentage), depending on the practical average day temperature.

In practice the graphic calendar and the percentage table are employed as follows: The date of first infection is determined theoretically from observed weather conditions, and, using the graph of incubation fluctuations, the day of the first appearance is marked on the abscissa. The value of the incubation period already elapsed in relation to future disease development is determined by the reciprocal of the equation of Müller's curve from the moment of first infection. A value near 100 per cent indicates that the incubation period is ended. If there is no indication of dry cool

weather with a minimum of 13° C at the end of this period, spraying should be carried on for two or three days prior to its end. From the comparison of the theoretical dates of downy mildew appearance with those of actual appearance the amount of error can be found, permitting more precise work on the vine treatment in the future.

Oltarjevski (1935) and Merjanian and Lipetzkaya (1936), in field and laboratory experiments on the effect of light (Oltarjevski) and temperature (Merjanian and Lipetzkaya), have also contributed much in reducing biological forecasting studies on *Plasmopara* to a mathematical basis. Oltarjevski (1935) has demonstrated that when vine leaves exhibiting the oil patch stage of the disease, but still devoid of conidia, are collected just after sunrise and kept in the dark, they develop conidial fructifications within seven or eight hours, while similar leaves kept in daylight but not in direct sunlight produce conidia after about 19 hours. Production of conidia was also delayed by gradually increasing the intensity of the light to which the leaves were exposed. Older oily spots required longer exposure to darkness, sometimes as much as ten to eleven hours, than newly formed patches to produce conidia. Minimum temperature between 10° and 13° C, if occurring just before sunrise, produces visible outbreaks of vine mildew.

Merjanian's and Lipetzkaya's (1936) work on lengthening or shortening of the incubation period was mostly concerned with temperature. They suggested that the shortening of the incubation period under the influence of high night and lower day temperatures might be due to a physiological effect on the parasite. In regions where during spring there are sudden and sharp fluctuations in day and night temperatures, the incubation period may be considerably shortened when night temperatures are higher and day temperatures are lower than normal for the season, the nocturnal rise being regarded as more important than the diurnal fall. Abnormally cold nights and abnormally warm days did not appear to affect the length of the incubation period. This incubation period is defined as the time from actual penetration of the host tissues by the germ-tubes produced by zoospores to the appearance of the conidia. Under favorable conditions of air humidity this may coincide with the formation of oily spots on the leaves. These studies permitted Merjanian and Lipetzkaya (1936) to devise

another mathematical method for determination of the actual length of the incubation period, viz.:

$$\frac{61°}{\text{Average daily "effective" temperature}}.$$

This divisor is calculated as follows: actual temperature minus the "critical" temperature for a given set of nocturnal and diurnal temperatures, or the minimum point below which the fungus is suppressed (Merjanian and Lipetzkaya, 1936). It was experimentally determined that duration of incubation period is determined by the sum total of degrees of "active" or "effective" average daily temperatures prevailing during the incubation period, or that temperature above the "critical" (minimum) points below which germination of the zoospores inside the stomata and the growth of intramatrical hyphae are completely supressed. This total was shown to range within the limits of 13° to 24° C, the average temperatures of Müller's curve, or from 58.9° to 62.6° F, giving a working average of 61° F. The above formula, therefore, is an expression of the interaction of temperature and length of incubation period.

SPAIN. In the treatment of vines for protection against mildew, Clemente (1934) describes an instrument, Präzisions Polymeter, which is used to indicate the opportune moment for treatment with fungicides. This instrument consists of a thermometer and hygrometer, the thermometer surmounting the round clock-like hygrometer. If there is a difference of less than ten degrees between the thermometric temperature and the humidity measured on the hygrometer, it is not probable that mildew will develop, but if the difference is above ten degrees, there is danger of infection. These observations are made an hour before sunset on the instruments which are usually installed in open fields but protected from the sun and climatic changes.

AUSTRALIA. A warning service is conducted on downy mildew of grapes (ibid., late blight section).

POTATO AND TOMATO LATE BLIGHT

Outside the United States.

HOLLAND. Forecasting and spray warning services were developed in western Europe about 25 years ago. Van Everdingen

(1926–27) analyzed the combined effect of several weather conditions on the development of *Phytophthora infestans* (Mont.) D By. and evolved four rules known as the "Dutch rules" upon which the appearance of blight was observed to hinge. They are:

a) Dew during at least four hours at night, i.e., night temperature below the dewpoint for this length of time.
b) A minimum temperature of 10° C (50° F) or above.
c) A mean cloudiness on the next day of 0.8 or more.
d) Measurable rainfall during the next 24 hours; at least 0.1 mm.

When all four conditions obtained in Holland, control measures were recommended.

A survey made in Holland in 1926 proved the validity of these Dutch rules. Based on them, a warning service was set up which has been carried out for the past 24 years (Post, 1950; Post and Richel, 1951). The Royal Dutch Meteorological Institute at de Bilt installed several special stations (Post, 1950; Post and Richel, 1951) with weather equipment to afford records of dry, wet bulb and minimum temperature data, amount of cloudiness noted at 8h, 14h and 19h, with rainfall measured at 8h. All these data are taken at a height of 40 cm. above ground level and, if possible, in, or in the immediate vicinity of, a potato field. The stations send messages by telephone or telegraph every morning when the weather fulfills the conditions of dewpoint and minimum temperature. The following day observations on cloudiness and rainfall are added. When conditions are right for an outbreak of potato blight, the warning service issues blight warnings by radio. Very satisfactory results have been obtained from this "cautionary service" (Van Poeteren, 1928, 1929*a, b;* 1931*a, b;* 1934; 1937; 1938; Van Everdingen, 1935; Post, 1950; Post and Richel, 1951).

In the past few years, in 1948 and 1949, a method was sought (Post, 1950; Post and Richel, 1951) which would make it possible to give warnings without using the special stations, for it was shown that in many cases the stations gave only a local and not a regional warning. Also, farmers asked the Institute to predict a critical period for the outbreak of potato blight. Although it was shown (Beaumont, 1947) that reliable warnings could be given, based on relative humidity and minimum temperature observations at the 40 cm. level, normal synoptic weather observations from the

regular weather stations were employed to give this prediction of the outbreak of blight. This method has two great advantages. The first is that all observations needed can be taken from the weather maps and from the synoptic stations which every hour send their observations to the Meteorological Institute. Secondly, from the farmers' point of view this method of warning is a regional warning. In some cases it is possible to predict a period in which the weather will fulfill the conditions of temperature and relative humidity so that farmers have one or two days more to spray their potato crop before the outbreak of blight. In many cases where critical periods were predicted locally, the prediction was followed by some rainy days, when spraying, of course, was not effective.

The criteria for such predictions are the result of a comparison of a great number of observations from 2.20 m. and 40 cm. levels. These criteria are (*a*) two consecutive days with a mean relative humidity of 82% or more (further investigation showed that potato blight also broke out when in one of the two days the mean relative humidity descended to 79%), the mean being taken from observations at 8, 14 and 19 hours; and (*b*) for one of the days, at least, the minimum temperature must be 10° C or more.

ENGLAND. For about the past 22 years English workers tested experimentally the Dutch rules for late blight forecasting (Beaumont, 1931, 1934, 1947). Under weather conditions obtaining in England the rules were generally satisfactory, although the blight did not appear as quickly as the rules predicted. In England dew formation and periods of high humidity with temperature sufficiently high, minimum temperature 50° F or over, are looked upon as insuring development of the blight (Beaumont and Hodson, 1930, 1931; Beaumont et al., 1932; Beaumont and Staniland, 1933, 1934, 1935, 1936, 1937; Wiltshire, 1931). Beaumont and Hodson (1931) added a fifth rule to those formulated by the Dutch to apply under conditions in England, particularly in Devon and Cornwall. The additional condition, or fifth rule, called for periods of not less than two days in which the relative humidity (at 3 p.m.) was higher than 75%. Even when air temperatures did not reach 50° F in the West Cornwall region, blight occurred after periods of high humidity (Beaumont and Staniland, 1933), the cumulative effects of high humidity compensating for lower temperatures.

According to the authors the humidity figure is a much more definite boundary, as it marks the line between spore production and absence of spore formation.

In 1937 (Beaumont and Staniland, 1938) these five rules were reduced to two, since equally good results were obtained from their use, viz.: (*a*) minimum temperature 50° F or over, (*b*) relative humidity not under 75% for at least two days. This modification of the Dutch rules was adopted for future use (Beaumont and Staniland, 1938) and has become the basis of experimental forecasting for blight conditions in England (Beaumont, 1947). Although the Dutch rules applied in southwest England to a certain extent, they tended to forecast blight appearance earlier than eventually happened (Beaumont, 1947).

There is still relatively little public plant disease forecasting being conducted in England (Gregory, 1950*a*). Warnings have been issued to farmers about future disease outbreaks by press notices and radio, notably by radio, for many years on the imminence of potato late blight. However, the Beaumont system (loc. cit.) is currently being tested officially to determine whether it can be adopted as a basis for a public warning system.

The key to the solution of late blight forecasting, according to Napper (1933), was considered to lie in the combined effect of weather factors on the water content of the host plant. The weather conditions upon which forecasting might be based are those which will bring about a high water content of the host tissues followed by a "drying wind" or sunshine to reduce water content of the conidia and induce germination. From the author's experiments it was found that conidia of *P. infestans* will germinate only when the water content of the host tissues has been reduced four to 18 per cent below the maximum. The effect of reduction in the water content of the host plant is to decrease the water content of the conidia by aproximately the same amount. Mycelial growth is also inhibited when the water content of the host is low.

SCOTLAND. In Scotland Grainger's (1950) experiments confirmed Beaumont's (1947) general theories on the temperature–humidity rule. Forecasts were all valid after the last days of June for the period 1944 to 1948. Since they were not valid before the

end of June, Grainger specified this time as the "zero time" of validity for the forecasts in southwestern Scotland. Foister (1950) confirms that for the west and southwest of Scotland, Beaumont's temperatures and humidity rule is valid, to a very large extent, for a crop in the neighborhood of the reporting service. In the east and north areas consistent data have not been obtained, the data being "marred" by the appearance of blight within a very few to ten days after the forecast instead of after the longer period experienced by Beaumont (1947). In these areas forecasting seems to be almost a problem of locality, since crop environment, combined with relatively large topographical variations, even within one area, tends to give individuality of disease conditions to each field, and individual forecasts, of course, are beyond the scope of a forecasting scheme.

Successful forecasting of the first appearance of blight and of weather suitable for subsequent attacks would be invaluable for timing protective sprays to diminish spread of blight to tubers and would reduce the level of tuber decay in most years. Similarly forecasting the first appearance of blight in the Ayrshire district of Scotland, where potatoes are grown for seed, would greatly reduce loss, as blight usually appears when the potatoes have reached the period of effective growth. At the present time only one station, Leudars, covers this district. However, seed growers are not disturbed by the fact that blight may kill the haulms completely towards the end of the growing season, thus acting as a cheap and natural alternative to chemical haulm destruction (Foister, 1950). Also, Van Everdingen's (1926) and Cook's (1947*a, b, c;* 1948; 1949) criteria on rainfall in relation to haulm blight forecasting would not hold directly under Scottish conditions, since spraying is uneconomical because haulm blight usually occurs too late to affect the yield. The forecast of heavy or continuous rain might be helpful by allowing growers to burn off the tops before the rain encouraged extensive tuber infection. A destructive spray, however, applied just before blight appeared, would prevent establishment of blight on foliage at lifting time, prevent heavy infection of tubers and loss in storage, and would allow normal digging procedures to go on unhampered. This spray would be very effective, particularly when there is sufficient rain in late season to wash the spores down to the tubers.

FINLAND. Rainio (1937) reports that difficulties involved in timing aplication of sprays can be overcome by provision of an adequate number of observers and by preparation of special isophane maps indicating the relationship between climatic factors and development of blight on a given variety at a certain time in different parts of the country.

GERMANY. The German contribution to late blight forecasting in this period was in basic studies of the effect of environment on the blight fungus. Müller (1931) points out that the intensity and extent of an epiphytotic are conditioned by the weather conditions before attack, not while the disease is actually in progress, spread of fungus, however, being governed by the reaction of the host as well as by meteorological conditions. Fluctuations in relative atmospheric humidity (Orth, 1937) are more detrimental to sporangial development than changes of temperature within a fairly wide range (2° to 34° C).

GREECE. Van Everdingen's (loc. cit.) rules were found to obtain in Greece during a severe epidemic of potato blight which occurred near Chalcis on Euboea Island (Zachos, 1950). In the twenty-day period when the disease was severe in 1949, favorable weather conditions for disease development prevailed on four days, with rainfall on three other days contributing to disease extension.

RUSSIA. Russian workers followed Van Everdingen's (loc. cit.) rules in forecasting late blight development (Naoumova, 1935). The length of the incubation period of the disease was found to be dependent mainly on minimum, mean and maximum temperatures prevailing on three days following the "critical" day, with relative humidity not affecting the length of this period appreciably. From a statistical analysis of the problem a "nomogram" was constructed by which the time of appearance of late blight could be determined from these data.

FRANCE. The vine mildew observer type system, including issuance of spray warnings, was utilized also in forecasting late blight development in France. In 1932 Dufrenoy (1932; Plant Path. Sta., 1932, 1933) proposed four conditions for the infection of potato plants. They were similar to those of the Dutch rules and were conditions generally favoring germination of zoospores. These conditions are:

a) During the night the temperature must not go lower than 10° C (optimum temperature for germination of zoospores between 10°–13°).

b) The leaves must remain covered with dew at least four hours of the day following the night dew.

c) The sky must remain cloudy, i.e., 0.8 of the sky should be covered with clouds.

d) There must fall at least 0.1 mm. of water in the form of rain.

Viennot-Bourgin's (1934) data, however, showed that under exceptional climatic conditions and even in the absence of Van Everdingen's requirements for late blight (loc. cit.), serious attack may take place at an advanced stage of growth when the infection tends to become rapidly localized in the ripening tubers. Limasset (1939) found that blight continued to spread, even when humidity was under 75% and Beaumont's two rules were not satisfied.

NORWAY. During World War II a warning service was established for *Phytophthora infestans* on potatoes, using the English modifications of the Dutch rules (Jørstad, 1950). The method was employed from 1941 to 1947 but met with small success, owing to the varying climatic conditions in the mountainous country of Norway.

Looking to the future, the American method (Cook, 1947*a, b, c;* 1948; 1949; Nugent, 1949, 1950) will be studied, and after preparatory investigations from 1951–1953 Norway plans to establish a forecasting service for late blight, beginning in 1954.

BRAZIL. Apparently nothing has been published in Brazil on the subject of plant disease forecasting. However, results of studies on forecasting tomato late blight will soon appear in the " Arquivos do Instituto Biológico " of the São Paulo Instituto Biológico. Bitancourt (1950) reports that A. C. Andrade of the Institute has analyzed the meteorological records of several localities in the State of São Paulo for the past 14 years and has found that a critical period of mean temperature below 21° C and rainfall above 30 mm. for a one-week period occurred a few weeks before the appearance of tomato late blight as recorded in the Institute's files. This has taken place five times since 1937. Critical periods occurred only twice without a corresponding record of late blight. No records of the disease exist when the critical period did not occur. Andrade

concludes that prediction of an epiphytotic can be made on the basis of the occurrence of two consecutive weeks or four alternate weeks of low temperature and high rainfall in the State of São Paulo. He plans in the future to make announcements advising spraying whenever these weather conditions endure for a whole week.

PERU. In Peru (de Segura, 1950) studies have been undertaken on the meteorological conditions influencing the incidence and development of *P. infestans* on potato with the purpose of establishing a service for prognostication and prevention of diseases and pests of cultivated plants. This is extremely important in a nation so dependent on its agricultural production.

Following an extremely virulent attack of *P. infestans* on potato in 1947, growers were forced to employ various fungicides in subsequent years, but equally important was knowledge of the opportune time to spray or dust. Under conditions obtaining at Lima, the factors for initiation of late blight on potato comply with those established by Beaumont and Staniland (loc. cit., late blight forecasting in England). In 1945, a year without blight in Peru, it was noted that the relative humidity was almost permanently below 95% and that very few days had nocturnal hours with 96%. In April and May the humidity averaged less than 75%, rising and falling in the months of June, July, August and September, and the first 15 days of October, the average maintained near 75% with few exceptions. In the last half of October the average humidity was below 75%. In contrast, in 1949, a year of intense infection, the relative humidity was 100% during many hours on all nights. In 1947 and 1948, also blight years, the nightly relative humidity was between 98 and 100%. Since in both blight and non-blight years the relative humidity for the majority of days was on the average near 75%, the daily nocturnal relative humidity is held to be more important under Lima conditions. With nightly humidity of less than 95% there is no danger of blight infection. With relative humidity ranging above 95%, the possibility for epiphytotic attack is indicated. In other words, a nocturnal relative humidity of less than 95% with considerable variation in daily temperature produces conditions unfavorable for blight. In contrast, high nocturnal humidity, with little variation in daily temperature and with temperature minima between 10° and 13° C, provokes a heavy attack of *P. infestans*.

AUSTRALIA. While there is no formal plant disease forecasting scheme in operation in Australia (Magee, 1950), warnings are issued for late blight of potatoes and tomatoes when seasonal conditions are favorable for development of the disease. These warnings are issued by agronomists and other officers stationed in the region through the country press or over the radio agricultural programs. They serve as reminders to growers on application of sprays for control.

JAPAN. Considerable attention is being given to the study of late blight of potato in Japan (Salmon, 1951). Appearance of the disease and its progress northward are noted in various parts of Japan, with appearance serving as warning of possible damage to the north. However, the correlation is generally not sufficiently good to serve as a basis for prediction except in Shizuoka Prefecture, where appearance of the disease is a reasonably reliable index of occurrence some three weeks later in the more northerly and generally higher Prefecture of Nagano.

In the United States.

Basic studies on the late blight organism itself, its epiphytology and the effect of environment on development and spread of the disease have formed the background for the prediction of late blight and the conduction of a warning service in the United States.

About 20 years ago the first spray warning service was initiated in Maine in 1931 (Bonde, 1932). Phenomenal growth in number of participators occurred in three years, from 81 in 1931 to 311 farmers with 2,605 acres in 1932 (Maine Bull., 1932), and increasing to 3,000 in 1934 (Maine Bull., 1934). The service issued spray warnings and notes on existing disease conditions in the State.

In South Carolina, Moore (1937), in his analysis of weather records for the prior 20 years in relation to blight, found that development of infection appeared not to be materially affected by mean temperature and relative humidity but to bear some relation to the amount and distribution of rainfall during the growing season. From rainfall data accumulated during the early part of the season, it was thought possible to predict the time and frequency of spray and dust applications. Amount of rainfall deemed necessary for late blight outbreaks was 3.5 inches distributed over

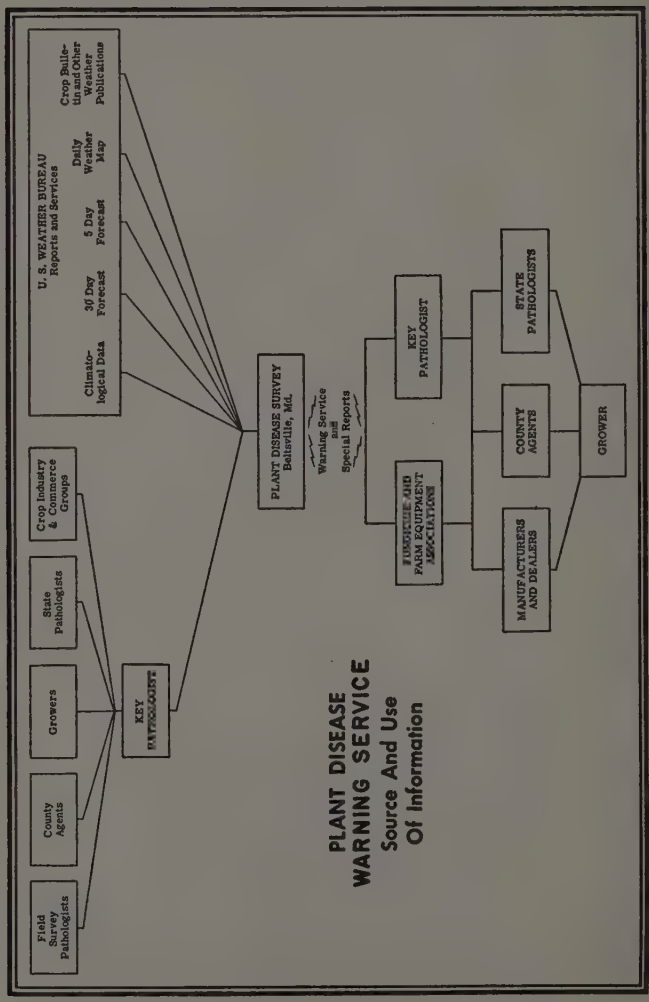
nine days in March, April or May, with five or more days having 0.2 inch or more of rain.

Following the severe blight epiphytotic of 1946, Cook (1947*a, b*) made a study of the relation of temperature and rainfall during the preceding 17 years to blight on potatoes and tomatoes in eastern Virginia. He concluded that the critical period for blight development in that area started on May 8th. The cumulative mean rainfall lines, starting May 8th for the years when blight was severe and when blight was absent or unimportant, were plotted, and a median line between the two was designated the critical rainfall line. The critical temperature was taken as 75° F. He found that severe epiphytotics were likely to follow a two-week period when the rainfall was continuously above the critical rainfall line and the temperature below 75°. Cook (1949) later expanded the analysis of the weather in relation to late blight to 31 years (1917–1947) at Norfolk, Virginia, and at Charleston, South Carolina. He concluded that the forecasting method during that period would have been 84 per cent correct for the Norfolk area and 81 per cent accurate for the Charleston area and would have made it possible to eliminate unnecessary spraying in 77 and 58 per cent of the years, respectively, in the two areas. The errors would have been entirely in predicting late blight years when it failed to develop to an epiphytotic degree. Cook (1949) described a method for quickly determining the beginning of the critical blight period by means of a chart of the moving seven-day average total rainfall and moving seven-day average mean temperature for the blight and non-blight years. Cook (1947*c*, 1949) and Nugent (1949, 1950) accurately predicted the blight situation in eastern Virginia in 1947, 1948 and 1949. Cook (1947*c*) estimated a saving of $2,000,000 by eliminating unnecessary spraying and dusting in eastern Virginia in 1947. In 1948 Cook (1948) made predictions on the late blight situation at Charleston, South Carolina, from his Norfolk office, based entirely on the official U. S. Weather Bureau reports and the critical rainfall and temperature chart for that area. However, Wallin and Waggoner (1949) reported that Cook's critical cumulative rainfall line method did not differentiate blight from non-blight years in their study of data for six stations in northern Iowa. Hyre and Horsfall (1951) collected and analyzed G. P. Clinton's records on the occurrence of late blight from 1902 to 1937, subse-

quent records of the Connecticut Agricultural Experiment Station, and rainfall and temperature data for Hartford and New Haven, Connecticut, from the Climatological Data of the United States Weather Bureau. Using Cook's (1947*a, b;* 1949) method, weekly mean cumulative rainfall in inches and the critical rainfall line were determined for the 49-year period prior to 1950. Their analyses led to the conclusion that it is possible to predict the probable occurrence of late blight on potato foliage in Connecticut on an area basis with about 80% accuracy by means of the critical cumulative rainfall line and weekly mean temperatures. These data corroborate Cook's findings (loc. cit.) but are different from those of Wallin and Waggoner (1949) in Iowa. In the Atlantic Coast area Hyre and Horsfall attribute success of Cook's method to the occurrence of fairly uniform primary inoculum potential from year to year, whereas in the reasonably blight-free areas of the Midwest the primary inoculum potential is quite variable.

Along with these individual research studies, the work of I. E. Melhus (1945), as Chairman of a war-time committee on potato late blight, was the forerunner of a nation-wide disease forecasting service in this country. In 1942 the loss from potato blight was 25,000,000 bushels. To avert such losses and to provide for quick and effective control measures utilizing readily available materials, a plan, based on a 27-year analysis of Iowa weather and late blight outbreaks, was put into operation in 1943 throughout the upper Mississippi Valley. Given the weekly temperature and rainfall of the potato-growing areas and assuming the presence of inoculum either from planting of infected seed or occurrence in field plants, on cull piles near warehouses and on dump piles near towns and villages, forecasts could be issued from a central source where all reports and data had been received and compiled. Seventy degrees F was set as the temperature above which growing conditions would not be highly favorable for late blight to develop initially.

With the end of the war and the merging of many grower, industry and scientific interests in this problem, impetus was given to the formation of a national warning service under the direction of the Plant Disease Survey of the United States Department of Agriculture. The particularly destructive epidemic of tomato late blight in 1946 was the deciding circumstance for establishing this program. Besides late blight on potato and tomato, warnings on the


PLANT DISEASE WARNING SERVICE
Source And Use Of Information
Field Survey Pathologists
County Agents
Growers
State Pathologists
Crop Industry & Commerce Groups
KEY PATHOLOGIST
U. S. WEATHER BUREAU Reports and Services
Climatological Data
30 Day Forecast
5 Day Forecast
Daily Weather Map
Crop Bulletin and Other Weather Publications
PLANT DISEASE SURVEY Beltsville, Md.
Warning Service and Special Reports
FARM EXTENSION AND FARM EQUIPMENT ASSOCIATIONS
KEY PATHOLOGIST
STATE PATHOLOGISTS
COUNTY AGENTS
MANUFACTURERS AND DEALERS
GROWER

occurrence of two additional downy mildew diseases, tobacco blue mold (*Peronospora tabacina* Adam) and curcurbit downy mildew (*Pseudoperonospora cubensis* (Berk. & Curt.) Rostow.) are also included in this warning service.

The organization by which the warning service obtains and relays reports on disease occurrence is clear from the accompanying chart. A "key pathologist" is responsible for the collection and use of information within each State, and also in the Canadian Provinces that take part in the warning service. Detailed accounts of the organization and progress of the service for the past five years have been published (Miller, 1947, 1948; Miller and O'Brien, 1948, 1949*b*, 1950; Miller and Wood, 1947*a*). At present the warning service does not itself predict occurrence, but merely furnishes the information for the purpose of local forecasts. However, general forecasts for late blight in the North Central States on an experimental basis have been very accurate (Wallin, 1951).

In investigations to improve the criteria for prediction it has been shown that spore traps have little practical value for forecasting the downy mildew type diseases covered in the program and that it would be hazardous to rely upon them for timing of a disease control program (Hyre, 1950). It has also been demonstrated that successful initiation of late blight can occur when temperatures are 75° F or less each day for eight days and the relative humidity is 90% or more for ten hours each day; and that temperature and humidity records from inoculated plots might permit prediction of the rate of spread of late blight, once primary infection has been initiated in the field (Wallin and Waggoner, 1950). Wallin (1951) has also demonstrated with experimental forecasts that conditions can be considered favorable for sporulation, spore germination and host infection if the temperature and relative humidity for ten or more consecutive hours is 70° F or less, and 95% or more, respectively.

SOME GRAIN CROPS DISEASES

BACTERIAL WILT OF SWEET CORN. The effect of environmental conditions on plant disease development again proved the basis for reliable prediction of outbreaks of bacterial wilt (*Bacterium stewartii* E. F. Sm.) of sweet corn. Stevens (1934) in the United States noted the association of a warm winter, or a series of warm

winters, with serious outbreaks the following spring and summer. During a warm winter ideal conditions obtain for the overwintering of the adult flea beetles in whose bodies the bacteria of corn wilt hibernate, thus ensuring sufficient inoculum for the build-up of an epidemic the following growing season.

During the latter half of the 1930's experimental general forecasts (Stevens and Haenseler, 1941) were published, based on indexes derived from the sum of monthly mean temperatures for the months December to February. An index below 90 usually indicated that the disease would be absent; over 100 would indicate presence of the disease in destructive amounts; and between 90 and 100 would indicate intermediate conditions. After these general forecasts had proved the extreme accuracy of the predictions, they were discontinued, since the method required no complicated bases of data or calculations and could very easily and more quickly be applied directly to specific locations by State pathologists.

Current reports for the years 1949 and 1950 (Poitras and Stevens, 1949; Pendleton et al., 1950; Boewe, 1950) have confirmed the correlation of warm temperatures of the preceding winter with abundance of infection. Based on the warm winter temperatures of 1949–1950, Boewe (1950) accurately forecast that the disease would probably occur much farther north in Illinois and be much more destructive than in 1949. Observations indicated also that the leaf blight phase of the disease in field corn could be predicted also on the basis of winter temperatures.

WHEAT LEAF RUST IN THE UNITED STATES. In the past decade Chester developed a system for forecasting the severity of wheat leaf rust (*Puccinia rubigo-vera* (D.C.) Wint. var. *tritici* (Eriks. & E. Henn.) Carl.) in Oklahoma, which has been distinctly successful (Chester, 1942, 1943, 1944, 1950; Chester and Larsh, 1945; Chester and Preston, 1946, 1947, 1948; Chester and Wadsworth, 1949; Young, Jr., and Wadsworth, 1951). The basis for the forecasts was an extensive analysis of the overwintering and early spring renewal of the rust correlated with late winter and early spring weather conditions. During the last week in March extensive surveys are made to determine how State-wide in application are the intensive studies. The reasoning behind the forecasts is that (*a*) the principal source of rust in Oklahoma is inoculum from overwintering local infections; (*b*) the weather of December

through February, and especially of March, is critical in determining the spring renewal of the rust; (*c*) the level of rust intensity on April 1 is the principal factor in determining destructiveness from April to harvest in June, since the number of generations of rust increase is limited in this period of time; (*d*) weather in Oklahoma is rarely a factor in limiting rust development after April 1st. Every forecast on these bases has been accurate and has been applicable usually throughout much or all of the wheat areas to the north. The forecasts have materially helped farmers and grain elevator operators to plan for harvesting and disposal of the crop or its abandonment in favor of spring-planted summer crops.

LEAF, STEM AND STRIPE RUST OF WHEAT AND BARLEY IN JAPAN. For the past ten years research on forecasting epidemics of leaf rust of barley (*Puccinia hordei* Otth. (*P. simplex* Eriks. & E. Henn.)) and of wheat (*Puccinia rubigo-vera* (D.C.) Wint. var. *tritici* (Eriks. & E. Henn.) Carl. (*P. triticina* Eriks.)), stem rust of wheat (*Puccinia graminis* Pers.) and stripe rust of wheat and barley (*Puccinia glumarum* (Schmidt.) Eriks. & E. Henn.) have been conducted, based on spore counts, interaction of meteorological conditions and plant development (Salmon, 1951). Prediction fields, similar to those for rice blast forecasting (see below), are established at key points. In these fields susceptible varieties are seeded ten days earlier than normal, and 50 per cent more than the normal amount of nitrogen is applied. The standard charts prepared by the United States Department of Agriculture (Melchers and Parker, 1922) are used for measurement of degree of infection.

Current work includes studies to determine whether infection results from overwintered spores or from spores blown in from other areas.

RICE DISEASES IN JAPAN (Blast and Seedling Rot). For the past 24 years studies on forecasting rice blast (*Piricularia oryzae* Briosi & Cav.) have been conducted in Japan (Salmon, 1951), based on (*a*) overwintering of the fungus, (*b*) conidial production, (*c*) time of appearance and prevalence of conidia in fields, and (*d*) relation of weather to development of rice plants. Studies apply mostly to neck blast but leaf blast is also considered.

Overwintering of the fungus has been established in the Honshu and Hokkaido Prefectures, where it is determined by taking samples of rice straw from the inside and outside of straw stacks and

subjecting them to surface sterilization and exposure in a moist chamber at a temperature of 25° to 28° C, suitable for development of the fungus. Growth of hyphae and production of spores are recorded. Viability of spores is determined by germination or dye tests, using solutions of neutral red and methyl blue. Dead spores are dyed blue and living spores red. Appearance of conidia on exposed naturally infected straws is recorded under laboratory and field conditions and is later correlated with temperature, moisture and other meteorological conditions.

Concerning the first appearance and prevalence of conidia in the air, " prediction fields " have been established throughout each rice-growing prefecture. In each field is grown a variety highly resistant to blast, another of medium resistance, and a third very susceptible variety. First appearance is determined by collecting spores at an elevation of three feet in paddy fields and at a lesser elevation in nursery beds and determining the number microscopically. In permanent " prediction fields " in areas where rice blast is likely to occur, infected straw is scattered in the field and half of each variety is fertilized with nitrogen at the normal rate and half at 1.5 times the normal rate. Prevalence is determined by examining 25 hills in each plot within 15 feet of the center and is expressed as a percentage of the number of stems and necks examined. Results are correlated with conidial counts, meteorological conditions and stage of development of the rice plant.

Forecasts of neck blast are based largely on spore counts and weather, particularly temperature and number of hours of sunshine. A rapid increase in spore count for a week or ten-day period ending 25 to 30 days before heading usually means heavy infection and much damage, whereas a light increase or no increase indicates little damage.

From a phenological standpoint, delayed growth of the rice plant also increases susceptibility. The appearance of the rice head is also important, for a delay of more than ten days as compared with normal development indicates heavy damage. However, there is ample time for making forecasts, since the most effective period for treating neck blast extends from ten days before to ten days after heading.

Also the use of an additional variety has shown some promise in improving predictions of neck blast. An early Mongolian variety is often heavily damaged by blast before it appears on other varie-

ties and can be used as the index plant for prediction of blast on the other varieties.

Predictions of occurrence of seed, or seedling, rot of rice (*Achlya* spp. or *Pythium dissotocum* Drechs. (*P. oryzae* Ito & Tokunaga)) are based on the time of seeding as compared with normal and on the effect of air and water temperatures. Seedling rot is thought to occur when the air temperature rises after a prolonged period of low temperature. The danger is regarded as especially great if the water temperature falls to 13° C for several days.

ERGOT ON RYE. To prevent loss and devastation of human and animal life from development of ergot (*Claviceps purpurea* (Fr.) Tul.) on rye (*Secale cereale* L.), an investigation was undertaken in Russia following a serious outbreak of ergotism in the eastern provinces of European Russia in 1926 (Rojdestvensky, 1927, 1928). The main purpose of this investigation was to establish a method (Kossobutsky, 1929; Markhasseva, 1936) for computing and forecasting the incidence of ergot in rye fields prior to harvest. A knowledge of the amount of ergot present would enable central and local authorities to warn the population against the use of flour prepared from grain with a contamination in excess of that allowed by law, namely, 0.15% minimum admixture of ergot sclerotia in rye grain in the U.S.S.R.

Extensive data collected in eastern Russia from 1926 to 1928 were analyzed by the variational statistical method (Kossobutsky, 1929). His results confirmed the interaction established by Bakhtin (Morbi Plantarum, Leningrad, xiv, 1, pp. 11–27, 1925) of four factors, viz.:

P = incidence of infected rye plants in the field
Q = incidence of infected ears
D = number of infected spikelets in the ears
R = contamination of the grain with sclerotia in percentcentage of weight.

The results also demonstrated that the correlations between these factors are of such a high positive order that with the help of certain coefficients it is possible, with the numerical value of one factor, to calculate the others.

Of the two coefficients worked out by Bakhtin, $P/R = K_1$ and $Q/R = K_2$, only the first one is constant, while the second varies with the numerical value for Q. For numerical values of Q equal

to 1 to 15, 15 to 30, 30 to 50, 50 to 75, and 75 to 100%, the constant values arrived at by the author for K_2 are 15, 12, 9, 6 and 3, respectively.

Since a fairly large proportion of sclerotia falls out during harvest and transportation (Bondartzeff, 1929; Kossobutsky, 1929), a distinction is made between contamination of the grain with sclerotia before harvesting (R_p) and contamination after threshing (R_o). The first type of contamination is calculated by means of a complicated formula and the second is deduced from the first by means of the formula $R_o = R_p - (q + a)$ where q is the quantity of sclerotia which falls out and a is the quantity of rye in percentage of weight lost prior to threshing. The quantities q and a are variable, depending largely on date of harvest, method of reaping and mode of transportation. The value of R_o is of greater practical importance than R_p, since it represents the actual contamination of the commercial grain and allows warning the population of the danger of using flour from grain with excessive contamination. The value of $q + a$ is said to equal $\frac{1}{2} R_p$ but needs confirmation under different conditions. It was also proved that the values of D and R_p depend much more on that of Q than on that of P, and, therefore, it was concluded there is no useful purpose in establishing the value of P in general practice.

SUGAR BEET DISEASES

SCLEROTIUM ROLFSII SACC. INFECTION. Expected loss of sugar beets (*Beta vulgaris* L.) from the activity of soil-borne *Sclerotium rolfsii* Sacc. can be approximated by an examination of the population of sclerotia obtained from soil samples collected from growers' fields (Leach, 1938). This population is expressed as the number of viable sclerotia per square foot of soil to a depth of eight inches. In a 300 square foot area ten soil tube cores were collected on diagonals of the square, washed through a series of screens, the sclerotia recovered and germinability determined at 30° C on the surface of unsterilized peat soil in Petri dishes. Results indicated that there was a direct and relatively high correlation between population of viable sclerotia, determined before planting, and subsequent per cent infection of sugar beets. When 200 viable sclerotia per square foot invariably showed more than 15% loss of sugar beets, while fields with less than 100 per square foot usu-

ally showed less than 10% loss, disease population could be relied on as a guide to elimination of severely infested fields in advance of planting and permit planting of these fields with non-susceptible crops to reduce the sclerotial population.

BLACK ROT. The field occurrence of black root rot (*Aphanomyces cochlioides* Drechs.) of sugar beets may be forecast before planting time by a greenhouse soil infection test (Fink, 1948). Disinfected seeds are planted in soil from prospective beet fields. After 30 days the percentage of infected seedlings is recorded, and Fink's experiments have shown that these records are highly correlated ($r = +0.925$) with crop loss in the field ranging from 0 to 95 per cent.

CURLY-TOP. Carter (1930) made predictions of the amount of curly-top virus of sugar beets which were based upon studies of the leaf hopper vector (*Eutettix tenellus* Baker). His predictions were evolved from population and migration analyses. In this work data were gathered on the survival of host plants on the desert breeding grounds and hibernation, or overwintering, of the hopper. An extremely hot dry summer eliminated most of the plants on the breeding grounds and indicated favorable prospects of reduced insect numbers for the succeeding year. Also, it was found that periods of below-zero weather very much reduced hibernating populations.

YELLOWS. Forecasting the steady advance of disease destructiveness has helped tremendously in planning for yields and the subsequent operations of factories, manufacturing concerns, etc. In working with the sugar beet yellows disease in England, Watson et al. (1946) found that the effect of infection on the yield of sugar was linearly related to the amount of infection; in other words, that loss of sugar yield from infection was proportional to the percentage of infected plants, with no compensation for loss in infected plants from increased growth of other healthy plants. Also, the sugar yield decreased linearly with later date of infection, falling to values of practically zero at the date of harvest. Greatest loss of yield occurred in plots where all plants were infected at the earliest date at the end of June and showed symptoms in July. Loss in such plots amounted to half or more of their potential yield of sugar. Thus loss in yield increases with length of time a plant

is infected. Blencowe and Tinsley (1951) point out that reduction in percentage of plants infected obtained by closer planting might be of importance, as greater time would be needed to cause total infection on a closely planted crop than on a sparsely planted one.

Based on the data from these observations, agricultural staffs of sugar factories inspect and sample the growing crop, and then forecast the weight of the roots likely to be delivered at the factory. The results suggested to Watson et al. (1946) that an accurate estimate of the loss caused by infection could be made by estimating the rate of infection on a number of occasions and assuming a constant rate of loss for each week of infection. Their experiments indicated that this loss is about 5% for the yield of sugar; loss in the yield of roots has not been computed.

FORECASTING CRANBERRY KEEPING QUALITY

Stevens (1943), interested in a new approach to preservation of crops from rots, forecast with good accuracy the keeping quality of cranberries (*Vaccinium macrocarpon* Ait.) in Massachusetts from 1923 to 1928. His predictions were based on the following observations: When May and June are warm, July and August wet, and the crop unusually large, the most serious fruit decay occurs. The least loss occurs under the reverse circumstances of May and June cool, and July and August dry. Moderate loss occurred when either a warm May and June or a wet July and August occurred, or, in other words, when the predisposing combination was lacking. The number of rainy days in July and August, when the fruit is developing, is apparently more closely related to the keeping quality than the amount of rain. However, as noted in the years 1920 and 1928 when crops were sound, approximately the normal number of days with rain in July and August occurred, suggesting that abundant and well-distributed rainfall is not necessarily followed by an unusual amount of rot in the fruit unless other factors favor the development of decay. Between temperature and keeping quality there is a constant correlation, high temperatures during September and early October favoring decay of cranberries in storage. Important cranberry fungi begin active growth at 50° F. This temperature was thus chosen as the minimum point for the summation of " degree days " above this point for indication of expected decay.

RESEARCH CONTRIBUTING TO FORECASTING

Many different fields of plant disease research contribute greatly to the scientific basis of prediction, even though not directly concerned with forecasting as such. Studies on the epiphytology of plant diseases and the effect of environment on their development; mathematical and statistical analyses of infection phenomena; investigation of the physics of spore dispersal and the mechanics of disease spread; prediction of the health of individual seed lots; estimation of disease intensity; correlation of different expressions of disease; and appraisal of loss—all accumulate the increased knowledge of cause and effect that will give forecasting of disease incidence and development greater certainty.

We mention a few studies concerned in the broad sense with build-up of disease in which the investigators have found correlations enabling them to forecast future development or loss.

SPREAD OF POTATO VIRUSES IN RELATION TO APHID POPULATIONS. Studies in the field of infection phenomena, particularly correlation of factors in disease spread with the ultimate view of predicting health of stocks, have been conducted on the spread of virus leaf roll and rugose mosaic in relation to the size of aphid infestation (Davies, 1934; Murphy and Loughnane, 1937; Whitehead, 1943; Gregory, 1943). However, this relationship between aphid populations on the plants during the summer and spread of virus disease was not expressed quantitatively except by Davies (loc. cit.) who found that in North Wales the health of seed stocks was readily maintained when the maximum number of *Myzus persicae* Sulzer did not exceed 20 per 100 leaves, whereas when it exceeded 100 per 100 leaves the stock deteriorated. Later (Doncaster and Gregory, 1948) it was found that in years of heavy infestation by *M. persicae,* spread of both leaf roll and rugose mosaic was greater. With the accumulation of more data (Broadbent and Gregory, 1948; Gregory and Read, 1949) it became possible to correlate numbers of apterous and alate aphids with spread of disease and to relate spread of virus more accurately to counts of apterous aphids caught on traps.

From statistical analyses (Broadbent and Gregory, 1948; Gregory, 1948 (method); Gregory and Read, 1949; Broadbent, 1950) of studies employing sticky trap counts (Doncaster and Gregory,

1948; Broadbent, 1948; Broadbent et al., 1948) it was found that there can be large differences in spread of virus diseases between potato crops carrying aphid populations of similar size, or similar spread in crops with widely differing aphid populations, and that there is a general correlation between virus spread and aphid numbers when results from a number of crops are averaged. Recent work (Doncaster and Gregory, 1948; Broadbent and Gregory, 1948; Broadbent and Tinsley, 1951) has demonstrated that alate aphids instead of apteras play a large part in disseminating viruses within the crop as well as in the spread from crop to crop (loc. cit., Broadbent and Tinsley), and that the spread takes place early in the season before the apterous aphid population develops. From the number of aphids trapped during maximum infestation of the potato plants when a large proportion of the insects have developed wings and are leaving the crop and the known initial health of the crop, the average health of the crop the following year can be predicted (Broadbent, 1950). A formula exists (Hauschild, 1947) by which the health of a crop at leafing time can be estimated, based on initial health and the course of the aphid infestation. German workers hope to use such a formula in forecasting the amount of virus spread.

BLUE MOLD OF TOBACCO. From a study concerned with the incidence and build-up of tobacco blue mold (*Peronospora tabacina* Adam) in the tobacco-growing regions of the United States, two strong indications as to the amount of damage and the effect of weather in relation to the yearly fluctuation in severity emerged. During a survey of 2,000 plant beds scattered throughout the tobacco-growing area in the South (Miller, 1937), it was noted that the amount of damage caused by blue mold in a given locality semed to be related to the earliness of the first signs of infection. In addition, there appeared to be a close relationship between above-normal January temperatures in the southernmost tobacco-growing States and the build-up of the disease. Analysis of weather records of January temperatures at five southern locations in this region showed that yearly fluctuations in intensity of the disease (Miller, 1937; Miller and O'Brien, 1949*a*) have closely followed the deviation from the normal of January temperatures for the years 1931 through 1951. Earliness of appearance in the Quincy, Florida, and Tifton, Georgia, area occurred in those years

when above-normal January temperatures approached the optimum, 62° F, for mildew infection. Continuance of favorable weather conditions, of course, aided the development of the disease. In those years when January temperatures were lower, blue mold appeared late and caused little damage, and even if favorable weather conditions prevailed later in the year, actual damage was slight.

Stover and Koch (1951) point out in their study on the incidence of blue mold in Ontario that severe outbreaks of blue mold in that Province are dependent upon spore showers originating in the Kentucky-Ohio tobacco-growing regions of the United States. In the epiphytotic years of 1945 and 1946, it was noticed that heavy spore showers in Ontario were closely associated with severe outbreaks in the Kentucky-Ohio area. These unexpected and widespread showers usually cause general outbreaks before adequate control measures can be carried out. Complete routine spraying and dusting might be reliable in controlling the disease but the expense would be quite exorbitant. Since the interval between the appearance of blue mold in Kentucky-Ohio area and its appearance in Ontario is approximately two to three weeks, complete information on the severity and build-up of the disease in Kentucky would make possible the establishment of a warning system. This system would be based on the probability of spore showers occurring and on the current local weather conditions most likely to favor development of the fungus.

Analyses of this type have practical applications as a basis for prediction prior to more elaborate and precise epiphytological research.

BACTERIAL WILT OF ALFALFA. Disease progression as an index of the future of a perennial crop has been forecast in the case of bacterial wilt (*Corynebacterium insidiosum* (McCull.) H. L. Jens.) of alfalfa (*Medicago sativa* L.) from data supplied by Salmon (1930), Graber and Jones (1935), Wiant and Starr (1936) and Weihing et al. (1938). Here, too, the problem is concerned with a constant rate of loss, not merely over one season but several, until growing the crop in a given disease-infested locality is unprofitable. From Weihing's data, and that of others, the steady march of the disease, which eventually destroys all plants through

succeeding years until the stands become unprofitable, can be seen from the fact that each semi-annual stand count shows roughly 75% as many plants as in the previous count. Trials in Colorado (Weihing, 1938) showed that stands of most varieties of alfalfa were too thin for hay production at or near Fort Collins after the third or fourth year of harvesting, thus providing an estimate of the value of wilt-infested land for alfalfa growing.

TEXAS ROOT ROT OF COTTON. In Texas, Ezekiel (1938) found a good correlation between May–July rainfall and the amount of Texas root rot (*Phymatotrichum omnivorum* (Shear) Duggar) subsequently developing in cotton. Cotton losses can thus be forecast several months before harvest.

DETERMINATION OF NECESSITY FOR SEED TREATMENT. Miller (1940), in studying the dissemination of *Glomerella gossypii* (Southw.) Edg., causing damping-off of cotton seedlings in the cotton belt east of Texas and Oklahoma, found that the number and severity of lesions on seedlings resulting from germination of a given sample bore a direct relationship to the spore load of the sample. There also seemed to be a correlation, although not complete, between high spore load and low percentage of germination of the cotton seed lots.

Miller and Wood (1947*b*) report the work of the Emergency Plant Disease Prevention Project in Minnesota and the Dakotas. Seed of barley, oats, wheat and flax, originating in widely distributed regions of these States, were collected to determine whether the particular organisms present were types that could be controlled by seed treatment and whether they occurred in such concentration as to justify treatment.

SPREAD OF CHESTNUT BLIGHT. When the chestnut blight fungus (*Endothia parasitica* (Murr.) H. W. & P. J. Anderson), growing within the bark and outermost wood layers of the American chestnut (*Castanea dentata* Borkh.), had attacked approximately 80 per cent of the trees, lumbermen and farmers were usually aware of the need for prompt cutting. This class of 80 per cent infection of the trees was chosen as a desirable point in forecasting spread of the disease. Two methods were employed for predicting the time when a given area would reach this point. In one, the percentage of infection in a locality was multiplied by an annual factor,

giving the predicted period required for that stand to become 80 per cent blighted (Gravatt and Marshall, 1926). The second method consisted of plotting the extension of the 80 per cent zone at the same rate it was known to have advanced in the past. In extending to the southwest across the State of Virginia, this rate was approximately 24 miles a year.

The accuracy of these predictions was limited by various circumstances, including the nature and scope of the surveys, the extent to which average conditions prevailed and the presence or absence of large spot infections. In general, a large part of the chestnut-blighted stands were presumed to be dead within two to five years after attainment of the 80% infection stage. There were a few trees, known to have been killed by blight before this time, and others assumed not to be dead six years after the 80% stage was reached.

FORECASTING TIMBER VALUES. In the field of estimating forest yields, the important work of forecasting timber decay cannot be overlooked. Hepting (1941) found a high correlation between fire wounds and rot. From curves and a formula relating age and width of the wounds to the amount of butt cull, the amount of cull at time of surveying could readily be determined and future cull predicted.

Another case in which external signs of defects indicate internal decay is cited by Zillgitt and Gevorkiantz (1938). By use of a table correlating 31 types and degrees of external defect with amount of internal decay, it is possible to determine cull in northern hardwoods, particularly sugar maple.

Tremendous savings in expense and timber can thus be effected by methods permitting knowledge of amount of decay volume and its effect on optimal cutting time to avoid serious loss.

INFECTION PHENOMENA. In the field of infection phenomena studies, an understanding of disease spread can be achieved and reliable bases for predictions can be built up from the work on the dispersion of spores (Blackman, 1942; Bonde and Schultz, 1943; Gregory, 1950*b*, 1951; Stepanoff, 1935; Wilson and Baker, 1946; Wolfenbarger, 1946), especially that which deals with the mathematics and methods of estimation (van der Planck, 1946, 1947, 1949*a*, *b*; Gregory, 1948; Waggoner, 1951).

Waggoner (1951), working on the aerial dispersion of *Phytophthora infestans* (late blight) spores, derived an expression for spore deposition as a function of distance, x, from a point source; source strength, Q_o; and the proportion, p, of the spores settling out as spore clouds passing over a unit area. His hypothesis for spore concentration was transformed into a formula for disease distribution:

$$D = \frac{0.135p(Q_o/k)}{x^{15/8}} e - 6.78px^{1/8}$$

This formula was tested by field experimentation on the proportion and pattern of disease development on potato leaflets around a primary source of inoculum. The observed pattern of disease occurrence, when compared with Waggoner's theoretical parametric values, proved the validity of his hypothesis.

Gregory (1948) has drawn attention to the possible misinterpretation of results that may come about when per cent present or absent of an organism is used as the measure of disease incidence. To infer gradients of spore density or numbers of insect punctures, it is necessary to apply a multiple infection transformation (Thompson, 1924; Gregory, 1945), as tabulated for ecological studies on *Ribes* by Fracker and Brischle (1944). This is essential when more than 20 per cent of the plants are infected (Gregory and Read, 1949). When the data measure disease factors, for example underdispersion or overdispersion, which are not randomly distributed, it is also necessary to find the correction factor, such as Blackman's K. For detecting overdispersion, or aggregation, which gives K greater than unity, van der Planck (1946) has provided a useful test employing the following formula for determining the number of random groups of two adjacent plants:

$$d = \frac{1}{n}\mu(\mu - 1)$$

where n = number consecutive plants examined in a sequence over a uniform area, μ = number of plants diseased.

Area gradients of disease are to be avoided by dividing the field into small blocks and applying the method to each separately.

DISCUSSION

The term "forecasting" for most people probably connotes a very technical and accurate prediction service on disease incidence

and crop loss. However, the work of forecasting plant diseases up to now has been built up largely on the activity of warning services which predict current probabilities of occurrence of diseases and their effects.

In our review the primary concern has been with the work of these warning services. The basis for their operation has been the correlation of environmental factors with disease appearance and spread. Knowledge gained from such analyses, when distributed to growers and used in conjunction with the other disease control measures, has contributed effectively to reducing the hazards of farming. No doubt, under many special conditions known only to the individual technical advisor and to the individual agricultural worker, local warning services are in action all over the world. In fact, every time a control measure is applied, the grower unconsciously predicts that his control measure is necessary, that it is timely and that it will result in increased production which would more than offset the cost of his application.

For any one disease, criteria used in one region, however carefully worked out, are seldom applicable in another, at least without modification. Limiting factors vary from region to region, depending on the kind and constancy of the various environmental components. The major limiting factor is the one that is most active at critical stages. In one area this may be temperature, in another moisture, in a third some other condition or possibly an interaction of factors. Source of the moisture may be rainfall, dew or irrigation. The influence of each environmental component is modified by variation in other factors. Moreover, optimal and limiting conditions are different at different stages of development of both host and pathogen. A slight change in a critical factor at a critical period will suffice to alter the whole future course of the disease. With all the possible variations and combinations of host × parasite × environment, it is easily understandable that each region possesses its own complex situation and must work out its own basic conditions for forecasting.

If warning services had not been conceived or extensively carried out, plant disease research leading to the further acquisition of knowledge concerning the relation of environment to disease development would be that much more delayed. However, at the moment there are encouraging prospects that vector- and spore-disseminated diseases will be more closely studied in regard to the

physical circumstances of their distribution; and further, that the highly technical research on insect movement and feeding; wind distribution of spores, some possibly tagged with radioisotopes; the physics of spore dispersal and patterns of deposition; the interaction of various environmental factors; and experiments on the dynamics of host–pathogen relations, will be reduced eventually to workable formulae upon which sound predictions can be made. Current meteorological research leading to the further development and increased precision of long-range weather forecasts probably will fulfill another prerequisite to the improvement of disease forecasting. Finally will come the task of translating the results of technical research concerning microclimate into working bases for growers which will enable them to utilize quickly and efficiently the means at their disposal, such as local weather maps and large area predictions.

SUMMARY

This review considers warning services in actual operation throughout the world. There are a number of these services and a variety of diseases covered.

Organized official warning services for various epidemic diseases were first instituted about 25 years ago. Even in early tentative periods of their operation, they reduced the ravages of diseases immensely. They are becoming increasingly recognized as an indispensable guide to the successful control of certain types of disease.

For a disease to be the subject of a warning service it must be important enough on the average to a large enough group for the service to be warranted. It is ordinarily a disease that varies considerably in occurrence so that one season's experience is not specifically applicable to another year; there must be some background of empirical or experimental knowledge about the conditions that favor or hinder its development and spread; and, finally, methods that will control the disease when properly applied must be known or the farmer must be able to reduce his loss in some other manner, such as planting earlier maturing varieties or other crops.

Operation of the services is simple: close watch is kept over all the conditions affecting infection and spread of the parasite, and growers are warned in time to take appropriate action.

Benefits from the warning services are increased efficiency and

reduced cost of control because the forecasts allow growers to time their operations properly or to omit them when not needed.

In general, the predictions are based on known facts about abundance and source of inoculum; environmental requirements of the parasite for infection, development and reproduction; manner of disease spread in relation to growth stages of the host; plus weather forecasts to show probable trend of disease development. In some cases formulae and charts have been devised for speedy translation of observed factors into disease prognostication. For diseases transmitted by insects, the source and abundance, manner and direction of spread, and feeding preferences of the vectors are considered, as well as environmental conditions affecting them in all their phases.

It has been found that for the same disease the criteria on which forecasting can be based may vary between regions because of different environmental combinations. Biological races of parasites and different varieties of hosts also are a cause of variation in host–parasite relationships and in reaction to environmental conditions.

Research now in progress in related fields will give greater precision to the knowledge on which forecasting is based.

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